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Stackable organic switches for reconfigurable switching hybrid systems

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This is a highly productive research project (13 papers in three years, on journals of Nature Photonics, Advanced Materials, Advanced Functional Materials, Angewandte Chemie International Edition, etc) aiming to (a) understand the potential of conjugated polymer based solar cell under simulated space radiation conditions, (2) develop and improving tandem polymer solar cell structures - constantly pushing the envelope of organic solar cell performance; (3) develop novel polymers for high efficiency OPV. In addition, we also conducted research in utilizing metal grating electrode to improve OPV light harvesting.

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Final Report

Stackable organic switches for reconfigurable switching hybrid systems

Grant Number: FA9550-09-1-0610 Program Director: Dr. Charles Lee

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We like to thank AFOSR for the support of this project. This is a highly productive research project (12 papers in three years, on journals of Nature Photonics, Advanced Materials, Advanced Functional Materials, Angewandte Chemie International Edition, etc) aiming to (1) understand the potential of conjugated polymer based solar cell under simulated space radiation conditions, (2) develop and improving tandem polymer solar cell structures - constantly pushing the envelope of organis solar cell performance; (3) develop novel polymers for high efficiency OPV. In addition, we also conducted research in utilizing metal grating electrode to improve OPV light harvesting.

The achievements are describes below.

1. Radiation effect and degradation mechanism study of polymer solar cells

Until recently, the focus of most solar technology development for space was towards more efficient, more radiation-resistant and increasingly powerful arrays. Two dominant performance metrics in the selection of solar array technologies are power/mass ratio (i.e. the amount of power that can be produced for each kilogram of total mass) and the volume of the stowed array as it is launched. Rigid, higher efficiency solar arrays come at the cost, however, of relatively high launch mass. These are important because of the mass and volume limitations on the launch vehicle that places the array into space, and the high cost of launching this limited mass and volume. The light weight and flexibility of PSCs are key advantages. It is these materials that will hold the key to inexpensive, easily deployed, large area, high mass-specific power solar arrays.

In the last three years, we collaborated with scientist from Air Force base and Univ. of New Mexico to investigate the potential of organic polymer solar cells for space applications. The results indicate that the disordered organic conjugated amorphous structure is in fact ideal for space applications. We have demonstrated the fundamental degradation mechanism behind

degradation of solar cells under high energy X-rays, gaining both a quantitative understanding and a physical understanding of the degradation process[1,2]. The work has also been highlighted by Nature Photonics (Nature Photonics 4, 580 - 581 (2010) doi:10.1038/ nphoton.2010.202). We have also shown that using smart interface design, the degradation in organic solar cells can be limited and controlled[3]. During the project, we also developed basic understanding of the carrier recombination mechanism in organic solar cells and derived the equation for lifetime of photo-generated carries (as measured from transient photo-voltage technique) from basic p-n junction theory giving new insights into the photo-physical process. This new understanding will additionally contribute to the development of basic science for these devices.

We also studied the issue of device stability,[4] which is taking center stage in organic photovoltaic research as the performance improves significantly in the last a few years. We studied the effects of oxygen and light on the degradation of charge-transport properties of the bulk polymer active layer are studied over short timescales. It is shown that although different processing techniques produce similar efficiencies for pristine devices, they result in different degradation rates. This variation in degradation rates is primarily due to slightly different morphology parameters, such as molecular packing or disorder in the film. Investigation reveals that the choice of processing for the devices should consider degradation rates as a critical parameter, not just the efficiencies of the pristine devices. It was found that degradation starts with broadening of the effective density of states due to photo-oxidation. Both transient absorption and charge extraction by linearly increasing voltage (CELIV) measurements show increase in disorder in the films with progressive degradation. It is suggested that annealing provides the necessary thermal energy to reduce the trap states by flattening out the energy landscape of the pristine films, improving not only the efficiency, as reported previously, but also slowing the degradation rates.

2. Solution process tandem polymer solar cells

In the past three years, our group achieved significant progress in advancing polymer solar cell efficiency through tandem structure. The tandem solar cell project has the following highlights:

1. We first demonstrated polymer tandem solar cells with a PCE of 5.8% by employing a p–n junction with a thin metal layer as an interlayer between the two subcells.[5] The role of the interlayer and several important issues of the tandem structure is addressed including optical

optimization, interfacial engineering, and accurate efficiency characterization (see image). It is revealed that the interlayer acts as a metal/semiconductor contact as opposed to a traditional tunnel junction in inorganic tandem cells.

2. A three-terminal tandem cell[6] based on two polymer bulk heterojunctions that have complementary absorption profile is demonstrated. This provides an alternative configuration to more effectively utilize the available pool of polymer solar cell materials. In this device configuration the two subcells are connected in parallel through a common semitransparent metal interlayer and an efficiency of 4.8% with short circuit current of 15.1 mA cm^{-2} is achieved.

3. Aiming at improving device stability and all solution process, we put significant effort in developing interconnecting layers for tandem solar cells. We first demonstrated a metal-oxide-only interconnecting layer,[7] which is expect to have better stability, and more importantly this enabled a novel inverted polymer tandem solar cell structure. Good electrical and optical coupling of the two sub-cells is achieved by using a carefully-designed MoO_3/Al/ZnO layer, which leads to a power conversion efficiency of 5.1%. We then demonstrated a robust inter-connecting layer that is optically transparent, electrically conductive, and physically strong. This new interconnection layer enables achieving high-performance tandem polymer solar cells with a PCE of 7.0%.[8]

4. Through designing high efficiency low bandgap (1.44eV) polymer and perfecting inverted tandem solar cell structure, we successfully demonstrated record high polymer tandem solar cell with 8.6% power conversion efficiency certified by NREL. The paper is published on Nature Photonics. [9]

5. In the beginning of 2012, we achieved 10.6 % NREL certified record OPV efficiency through collaboration with Sumitomo Chemical Corp. The paper has been accepted by Nature Communications.

In addition, other works conducted in the three years including:

(1) We developed new benzo[1,2-*b*:4,5-*b′*]dithiophene-containing polymer PBDTTBT[11] which exhibits a power conversion efficiency of up to 5.66 %. The high open-circuit voltage (0.92 V) originates from the low HOMO level of the polymer and the high internal and external quantum efficiencies over a wide spectral range. PBDTTBT is a promising donor material for application in polymer solar cells.

(2) We developed a simple imprinting technique to pattern the active layer of a low bandgap polymer solar cell.[12] Thin metal oxide/metal layers were then coated on the active layer to form a metal grating back electrode. By finely controlling the distance between the grating and active layer, about 10% short current enhancement (J_{sc}) is seen, without any obvious degradation to the open circuit voltage or fill factor. The power conversion efficiency increases from 7.20 to 7.73%, which is due to absorption enhancement from waveguide modes, Wood's anomaly, and plasmonic effects.

In summary, the project in the past three years is very fruitful. For the first time, we broke the 10% efficiency barrier of OPV, which came from our systematic efforts of interface engineering, tandem device structure and material innovation. We also further improved our understanding of radiation effect on polymer solar cell, and proposed clever interface scheme for future improvement of radiation hardness. These results formed solid ground for our new AFOSR grant to achieve 15% tandem polymer solar cell in the next funding period.

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